



US005881108A

United States Patent [19]
Herzberg et al.

[11] **Patent Number:** **5,881,108**
[45] **Date of Patent:** **Mar. 9, 1999**

[54] **ADAPTIVE PRE-EQUALIZER FOR USE IN DATA COMMUNICATIONS EQUIPMENT**

[75] **Inventors:** **Hanan Herzberg**, Morganville; **Ehud Langberg**, Ocean Township, Monmouth County; **Jin-Der Wang**, Ocean; **Jean-Jacques Werner**, Holmdel, all of N.J.

[73] **Assignee:** **Globespan Technologies, Inc.**, Largo, Fla.

[21] **Appl. No.:** **605,404**

[22] **Filed:** **Feb. 22, 1996**

[51] **Int. Cl.⁶** **H04B 15/00; H04L 25/03; H04L 25/49**

[52] **U.S. Cl.** **375/296; 375/285**

[58] **Field of Search** **375/296, 285, 375/346, 232, 233, 348, 278, 284, 221, 222, 231; 364/724.2, 724.19; 455/63; 333/18**

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,577,329	3/1986	Brie et al.	375/232
4,866,736	9/1989	Bergmans	375/290
5,008,903	4/1991	Betts et al.	375/296
5,251,328	10/1993	Shaw	455/73

5,263,051	11/1993	Eyuboglu	375/285
5,291,520	3/1994	Cole	375/296
5,513,216	4/1996	Gadot et al.	375/233
5,646,957	7/1997	Im et al.	375/234

OTHER PUBLICATIONS

United States Patent Application by Jin-Der Wang, entitled "A Hybrid Equalizer Arrangement for Use in Data Communications Equipment", Serial No. 08/322878, filed on Oct. 13, 1994.

United States Patent Application by S. Gadot et al., entitled "A Hybrid Equalizer Arrangement for Use in Data Communications Equipment", Serial No. 08/322877, filed on Oct. 13, 1994.

Primary Examiner—Stephen Chin

Assistant Examiner—Betsy L. Deppe

Attorney, Agent, or Firm—Thomas, Kayden, Horstemeyer & Risley

[57]

ABSTRACT

The problem of error propagation is resolved by using the communications channel to adapt a pre-equalizer of a transmitter, in response to changes in the communications channel. In particular, the pre-equalizer adapts to changes in the communications channel by processing an error signal that is communicated over a reverse channel by a corresponding receiver.

16 Claims, 4 Drawing Sheets

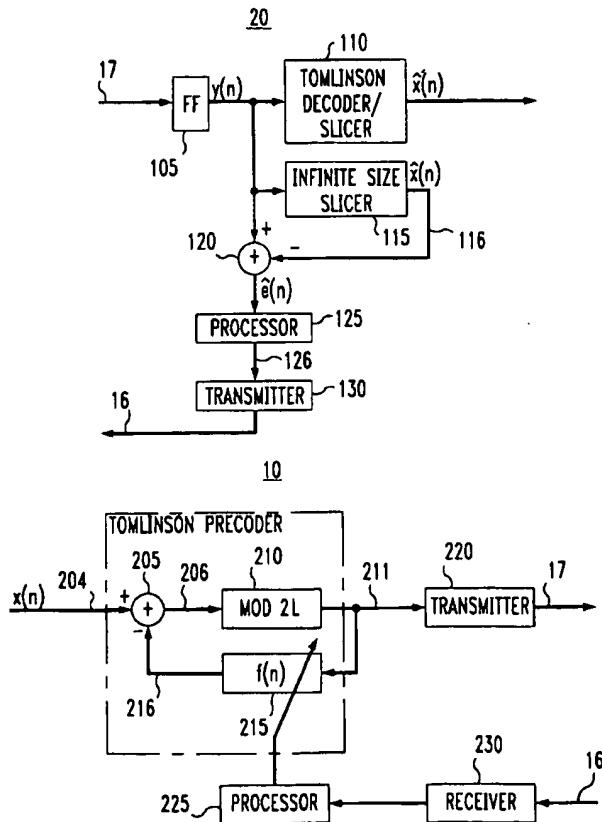


FIG. 1

PRIOR ART

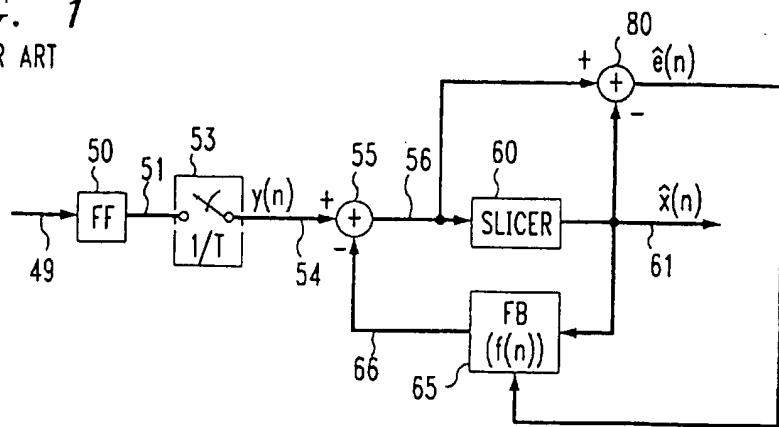


FIG. 2

PRIOR ART

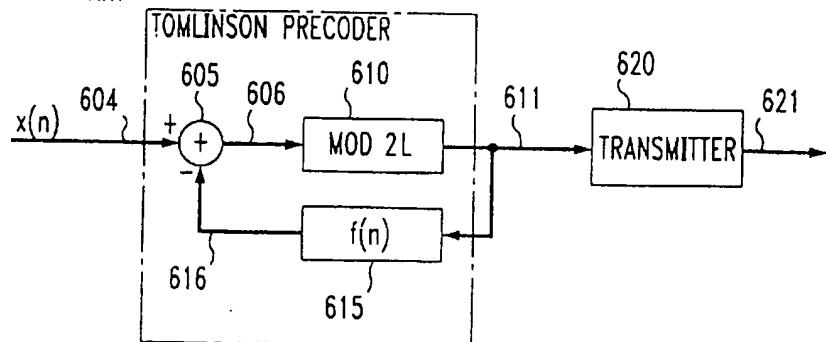
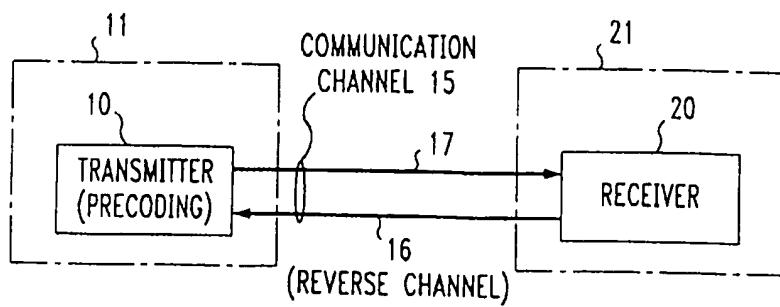


FIG. 4



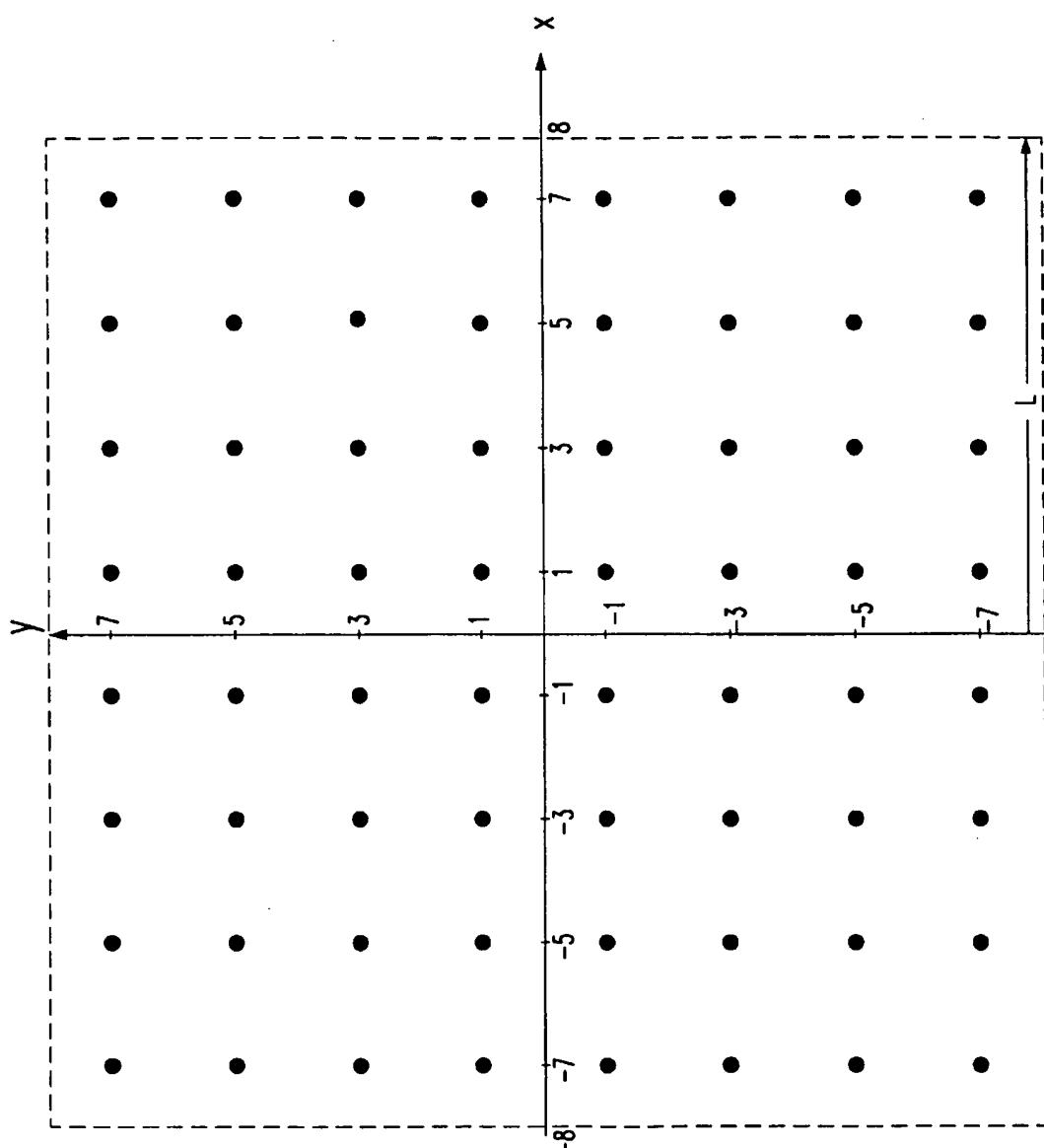


FIG. 3

FIG. 5

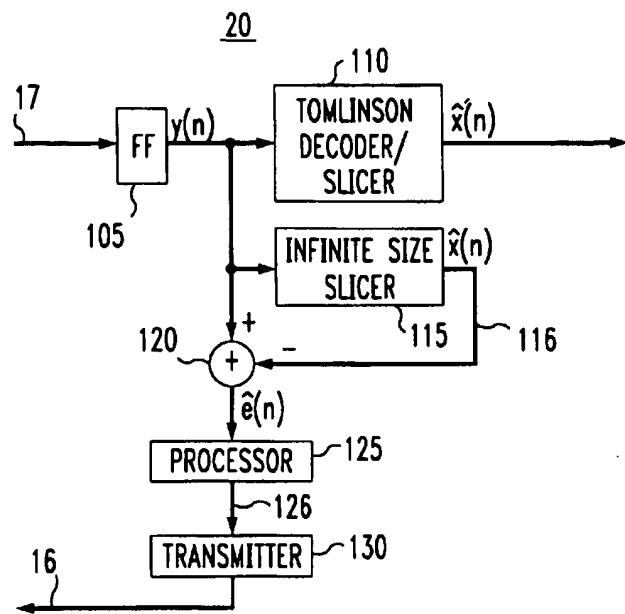


FIG. 6

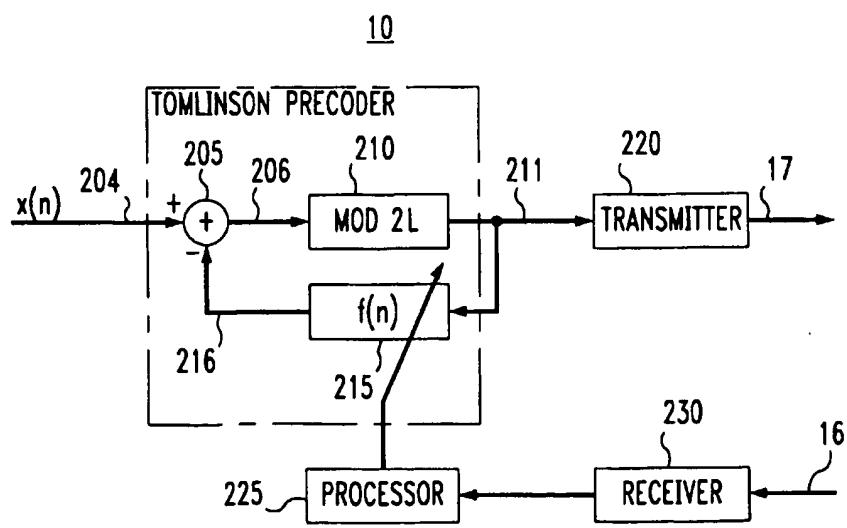


FIG. 7
COMMUNICATIONS PHASE

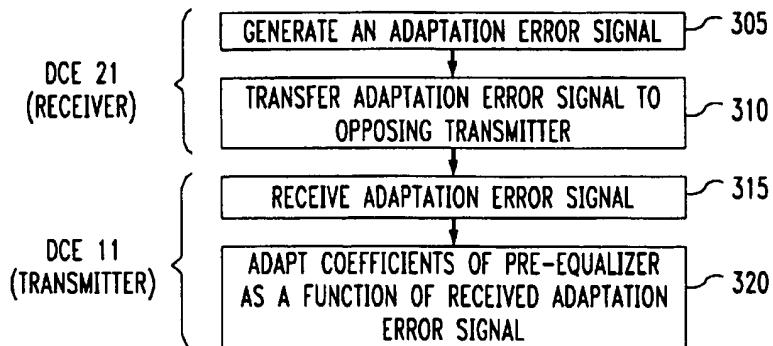


FIG. 8
COMMUNICATIONS PHASE

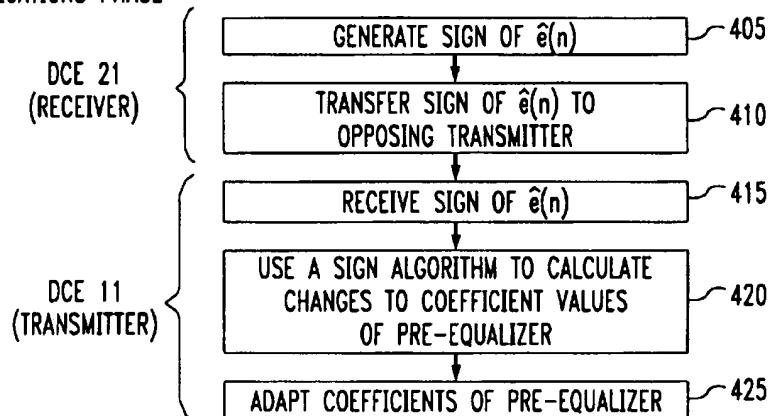
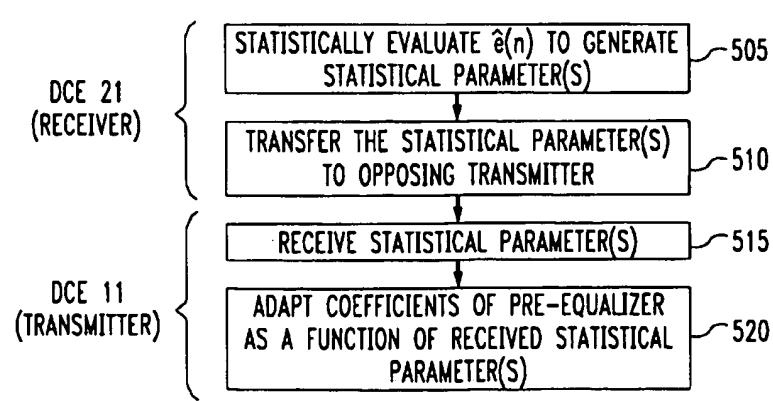


FIG. 9
COMMUNICATIONS PHASE



ADAPTIVE PRE-EQUALIZER FOR USE IN DATA COMMUNICATIONS EQUIPMENT

CROSS-REFERENCE TO RELATED APPLICATION

Related subject matter is disclosed in the co-pending, commonly assigned, U.S. patent applications of: J.-D. Wang, entitled "A Hybrid Equalizer Arrangement for Use in Data Communications Equipment," Ser. No. 08/322,878, filed on Oct. 13, 1994 and Gadot et al. entitled "A Hybrid Equalizer Arrangement for Use in Data Communication Equipment," Ser. No. 08/322,877, filed on Oct. 13, 1994.

BACKGROUND OF THE INVENTION

The present invention relates to data communications equipment, e.g., modems, and, more particularly, to the equalization of signals in a data communications system.

Conventionally, a receiver employs an adaptive decision feedback equalizer (DFE) to compensate for distortion introduced by the communications channel. However, the use of a DFE introduces "error propagation" effects in the receiver. As such, it is known in the art to use pre-equalization with modulo arithmetic (e.g., Tomlinson filtering) in the far-end transmitter in order to mitigate, if not eliminate, the problem of error propagation in the receiver. This pre-equalizer uses equalizer coefficient values communicated from the receiver, typically over a reverse channel. These coefficient values are generated in the receiver as the result of an initialization phase, or training, between the far-end transmitter and the receiver.

However, if the response, i.e., characteristics, of the communications channel changes significantly, the pre-equalizer will not be able to compensate for the error propagation problem in the receiver. As a result, a re-train is required so that the receiver can generate a new set of pre-equalizer coefficients, which must be then sent back to the far-end transmitter. Unfortunately, each re-train takes time to both calculate the pre-equalizer coefficients anew, and to communicate them back to the far-end transmitter over what is typically a low bandwidth reverse channel.

SUMMARY OF THE INVENTION

In accordance with the invention, the foregoing error propagation problem is solved by using the communications channel to adapt a set of coefficients of a pre-equalizer of a transmitter.

In accordance with an embodiment of the invention, a transmitter includes a pre-equalizer. The latter adapts to changes in the communications channel by using an error signal that is communicated over a reverse channel by a corresponding receiver. As a result, no re-trains are required and the error signal typically requires less bandwidth than a set of coefficient values.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a prior art DFE;

FIG. 2 is a block diagram of a prior art precoder;

FIG. 3 is an illustrative signal point constellation for use in the precoder of FIG. 2;

FIG. 4 is a block diagram of a communications system that embodies the principles of the invention;

FIG. 5 is a block diagram of a receiver, embodying the principles of the invention;

FIG. 6 is a block diagram of a transmitter embodying the principles of the invention;

FIG. 7 is an illustrative flow diagram for generating an adaptation signal in accordance with the principles of the invention;

FIG. 8 is another illustrative flow diagram for generating an adaptation signal in accordance with the principles of the invention; and

FIG. 9 is another illustrative flow diagram for generating an adaptation signal in accordance with the principles of the invention.

10

DETAILED DESCRIPTION

Before describing the inventive concept, a general overview of DFE operation is presented. (General information on DFEs can also be found in publications such as "Data Communications Principles," by R. D. Gitlin, J. F. Hayes, and S. B. Weinstein, Plenum Press, 1992.) FIG. 1 shows a prior art DFE that includes feedforward filter (FF) 50, sampler 53, adder 55, slicer 60, adder 80, and feedback filter (FB) 65. A received data signal 49 is applied to feed forward filter 50 for processing. Feedforward filter 50 whitens the noise present in the received data signal. The output signal from feedforward filter 50 is applied, via sampler 53, to adder 55, which, theoretically, subtracts the inter-symbol interference (ISI) estimated by feedback filter 65 (described further below). Adder 55 provides a signal, 56, to slicer 60. The latter selects a particular data symbol as a function of the mapping of the signal, 56, into a predefined constellation of data symbols (not shown) to provide $\hat{x}(n)$, which is an estimate of a transmitted data symbol, $\hat{x}(n)$. The signal $\hat{x}(n)$ typically represents a stream of data symbols occurring at a symbol rate of $1/T$ seconds and is provided for processing by feedback filter 65 and by other receiver circuitry (not shown) to recover the actually transmitted data. (For example, if trellis coding is used, $x(n)$ is subsequently processed by a Viterbi decoder).

Feedback filter 65 is a finite-impulse-response (FIR) having an impulse response represented by vector $f(n)$. As mentioned above, feedback filter 65 uses the estimate, $\hat{x}(n)$, of the transmitted data to predict the amount of ISI to remove from the received signal. Adaptation of feedback filter 65 is performed by using $\hat{e}(n)$ as an error signal, which is developed by adder 80. For illustration, it is assumed that a least-mean-square (LMS) algorithm is used to adapt the coefficients of feedback filter 65. As such, then the i -th coefficient ($i=0, 1, \dots, N-1$) at the time instant n , $f_i(n)$, is given by:

$$f_i(n+1) = f_i(n) + 2\mu e(n)\hat{x}(n-i) \quad (1)$$

where μ is the adaptation step size. (For simplicity, this description assumes the use of real filters and real data. However, the inventive concept is also applicable to complex filters and data as well.)

The DFE structure of FIG. 1 is based on the assumption that $\hat{x}(n)$ is a good estimation of the transmitted data $x(n)$. As long as this estimate of the transmitter symbol currently received is, in fact, correct, there is no problem. However, if the estimate of the currently transmitted symbol is wrong, then the feedback section adds this error to the next received symbol and error propagation occurs. As a result, as known in the art, a form of non-linear preceding is typically used in the far-end transmitter to minimize error propagation.

In precoding there are two phases of receiver operation. In the first phase, the "initialization" phase, the DFE of the receiver, illustrated in FIG. 1, adapts to a standard test signal, or training sequence, received from a transmitter (described below). This phase is also referred to in the art as a

"start-up," or "training" phase. Typically, there is no pre-coding of this test signal by the transmitter. Once the DFE adapts, the resulting set of coefficient values, $f_i(n)$, ($i=0, 1, \dots, N-1$), of the DFE are transmitted back to the transmitter, e.g., over a reverse channel!

At this point, the second phase, i.e., the "communications" phase is entered. In the communications phase, the transmitter now precodes the data before transmission using any of the well-known precoding techniques, e.g., Tomlinson preceding. An example of which is shown in FIG. 2. In FIG. 2, a data signal is applied to a Tomlinson precoder comprising adder 605, mod-2L element 610, and filter 615. Adder 605 subtracts a signal developed by filter 615, described below, from the data signal, $x(n)$. The output signal 606 of adder 605 is applied to mod-2L element 610, which performs as known in the art, to provide an output data symbol stream 611. For example, mod-2L element 610 maps the output signal 606 to a position in a signal point constellation. This mapping is performed using modulo $2L$ arithmetic, where L is the size of a signal point constellation. FIG. 3 shows an illustrative signal point constellation, where $L=7+1$. The output data symbol stream 611 is applied to transmitter 620, which develops a signal for transmission. The output data symbol stream 611 is also applied to filter 615, which filters this signal in accordance with the polynomial functions, or filter response vector, $f_i(n)$ using the above-mentioned set of coefficient values, $f_i(n)$, ($i=0, 1, \dots, N-1$). The latter is transmitted from the corresponding receiver after the above-described training phase.

Whatever precoding method is used, the preceding technique utilizes the above-mentioned coefficient values as determined during the initialization phase. Similarly, the receiver processes any received signal in a complementary fashion to remove the preceding, e.g., now incorporating a Tomlinson decoder. If the response of the communications channel remains constant for the transmission period, no further adaptation will be required since the precoding in the transmitter is equivalently performing the feedback function. As such, typically, the DFE section of the receiver is no longer used during the communications phase. However, in case of small changes in the response of the communications channel during the communications phase, a DFE feedback filter can be added to the receiver, initially set to zero. Unfortunately, when changes to the response of the communications channel are moderate or large during the communications phase, adding the DFE causes the error propagation problem that we tried to avoid by using the pre-equalizer in the far-end transmitter. In this situation it is known to either perform a re-train or a "quick retrain," as described in the above cross-referenced United States patent applications. In a quick retrain, only the dominate coefficients are re-calculated and sent back to the far-end transmitter over the reverse channel. In either event, each re-train takes time to both calculate the pre-equalizer coefficients anew and to communicate them back to the far-end transmitter over what is typically a low bandwidth reverse channel.

However, and in accordance with the inventive concept, we have realized that the foregoing error propagation problem can be solved by adapting the pre-equalizer to the changes in the response of the communications channel, using the reverse channel.

An illustrative communications system embodying the principles of the invention is shown in FIG. 4. The communications system comprises data communications equipment (DCE) 11, communications channel 15, and DCE 21. For simplicity only a single transmitter/receiver pair is

shown as represented by transmitter 10, of DCE 11, and receiver 20, of DCE 21. Transmitter 10 includes precoding and transmits a data signal to receiver 20, via communications channel 15, e.g., over primary channel 17. Receiver 20 communicates an adaptation signal, in accordance with the principles of the invention, to transmitter 10 over reverse channel 16. Although primary channel 17 and reverse channel 16 are shown as separate channels for simplicity, they are not so limited and represent any single, or plurality, of communications channels that enables transmission in both directions whether half-duplex, or full-duplex, over any number of different types of facilities (such as is found in the public-switched-telephone network). For example, reverse channel 16 can be a control channel that exists on a full-duplex primary communications link between transmitter 10 and receiver 20, thus enabling the inventive concept to also be practiced in the corresponding receiver (not shown) associated with DCE 11 and a transmitter (not shown), associated with DCE 21.

FIG. 5 is an illustrative block diagram of receiver 20 in accordance with the principles of the invention. The elements of receiver 20, other than the inventive concept, are well-known and will not be described in detail. Further, receiver 20 has been simplified to focus on the inventive concept, e.g., typically there is other receiver circuitry between feedforward filter 105 and communications channel 15. Finally, it is assumed that the communications system is in the above-described communications phase. That is, an initial set of equalizer coefficients has already been generated by receiver 20 and sent back to transmitter 10 over reverse channel 16. Receiver 20 comprises feedforward filter (FF) 105, Tomlinson decoder/slicer 110, infinite size slicer 115, adder 120, processor 125 and transmitter 130. A received data signal for processing is applied to feed forward filter 105, from primary channel 17. Feedforward filter 105 whitens the noise present in the received data signal to generate the output signal $y(n)$. The latter is applied to Tomlinson decoder/slicer 110, infinite size slicer 115, and adder 120. Tomlinson decoder/slicer includes circuitry that performs in a complementary fashion to the Tomlinson precoder of transmitter 10 to provide an estimate, $\hat{x}(n)$, of the actually transmitted data symbol, $x(n)$.

Immediately after switching to the communications phase, $y(n)$ is, ideally, ISI free (a small ISI level may still be produced due to misadjustment in the pre-equalizer) and the additive noise is close to white. Let $e(n)=y(n)-x(n)$. Since transmitter 10 incorporates preceding, transmitter 10 has an ideal reference for $x(n)$ —namely $x(n)$ itself. Therefore, and in accordance with the inventive concept, samples of $y(n)$ contain sufficient information for adapting the pre-equalizer of transmitter 10 and can simply be communicated back to transmitter 10 over reverse channel 16 (ignoring for the moment adder 120 and infinite size slicer 115). For example, a few bits per sample of $y(n)$ can be transferred to transmitter 10 every K time instants. However, it should be noted that the convergence rate will be slower than that of an adaptive DFE directly located in the receiver. This convergence rate can be increased to a degree by either increasing the data rate on the reverse channel (typically not an attractive systems option), or, where the data rate for the reverse channel is fixed, by reducing the number of bits required for each sample of $y(n)$.

Consequently, although samples of $y(n)$ could be directly sent back to transmitter in accordance with the inventive concept, it is preferable to accelerate the convergence of the pre-equalizer (described below) of transmitter 10 in a different fashion. In particular, and in accordance with the

inventive concept, an error signal is developed for transmission from DCE 21 to DCE 11 such that the number of bits required for representing the error signal is less than the number of bits required for $y(n)$.

As shown in FIG. 5, adder 120 of receiver 20 develops an approximation (denoted by $\hat{e}(n)$) of the error signal $e(n)$ by using an estimation of the transmitted data, $\hat{x}(n)$, which is developed by infinite size slicer 115. The latter is required since a form of modulo preceding is used. In particular, the estimate $\hat{x}(n)$ developed by Tomlinson decoder/slicer 110 may generate a large error at the boundary of the signal point constellation due to the modulo nature of the preceding. For example, the received signal point may be on one side of the constellation but the sliced signal point is on the opposite side, which would yield a large error value. Therefore, infinite size slicer 115 is configured to mathematically represent an infinite signal point constellation. That is, there are always more rows, and columns, of signal points presumed to be available when performing the slicing operation. Since $\hat{x}(n)$ is only used in this context to generate an error signal, it is of no consequence to the subsequent recovery of the actually transmitted data from $\hat{x}(n)$. Processor 125 processes the error signal estimate, $\hat{e}(n)$, in any one of a number of ways (some of which are described below) to generate an adaptation signal 126 for transmission back to transmitter 10 over reverse channel 16, via transmitter 130 of DCE 21.

FIG. 6 is an illustrative block diagram of a portion of DCE 11 in accordance with the principles of the invention. FIG. 6 is similar to FIG. 2 described above except for the addition of receiver 230 and processor 225. The latter receives the above-mentioned adaptation signal from receiver 230 of DCE 11, via reverse channel 16, and adapts the coefficient values, $f_i(n)$, ($i=0, 1, \dots, N-1$) of filter 215 to thereby alter the filter response vector $f(n)$ without performing a re-train. The processor 225 operates to generate an error signal as a function of the adaptation signal and a data signal that is not pre-coded, and then update values of the set of coefficients as a function of the error signal.

FIG. 7 shows a generalized method in accordance with the principles of the invention as described above. In this method, processor 125 of DCE 21 generates an adaptation signal in step 305 and transfers this signal to DCE 11 via reverse channel 16 in step 310. Processor 225 of DCE 11 recovers the adaptation signal from reverse channel 16 in step 315 and then adapts the coefficient values, $f_i(n)$, ($i=0, 1, \dots, N-1$) of filter 215 as a function of the received adaptation signal in step 320. Since the reverse channel data rate available for transferring information related to this adaptation is typically limited, an efficient adaptation method should be employed.

One method of generating an efficient adaptation signal in DCE 21 for adapting a pre-equalizer in DCE 11 is shown in FIG. 8. In this method, processor 125 of DCE 21 generates the sign of $\hat{e}(n)$ in step 405 and transfers the sign of $\hat{e}(n)$ to DCE 11 via reverse channel 16 in step 410. The value of the sign of $\hat{e}(n)$ is based upon one sample per data block of length K . Processor 225 of DCE 11 recovers the sign of $\hat{e}(n)$ from reverse channel 16 in step 415 and using any well-known sign algorithm calculates the changes to the coefficient values in step 420. (Sign algorithms are known in the art. For example, see V. J. Mathews and S. H. Cho, "Improved convergence analysis of stochastic gradient adaptive filter using the sign algorithm," IEEE Trans. Acoust., Speech and Signal Process., vol. ASSP-35, pp. 450-454, 1987; and E. Masry and F. Bullo, "Convergence analysis of the sign algorithm for adaptive filtering," IEEE

Trans. Inform. Theory, Vol. 37, pp. 1470-1475, 1991.) In step 425, processor 225 adapts the coefficient values, $f_i(n)$, ($i=0, 1, \dots, N-1$) of filter 215. In this case, the adaptation of the pre-equalizer coefficients takes the form:

$$f_i(n+1) = f_i(n) + 2\mu(\text{sgn}[\hat{e}(n)]\hat{x}(n-i)), \quad (2)$$

It should be noted that only one bit per sample is required for the case of a real filter, and two bits for a complex filter, which is typically well within any bandwidth constraints for a reverse channel. If μ is very small, the difference in steady state errors between the LMS and the sign algorithms is not large (when the convergence speed is fixed). As shown in equation(2), there must be proper synchronization between $\hat{e}(n)$ and $x(n-i)$ when updating the respective i -th coefficient.

Another method of generating an adaptation signal in DCE 21 for adapting a pre-equalizer in DCE 11 is shown in FIG. 9. In particular, processor 125 statistically processes $\hat{e}(n)$ to generate at least one statistical parameter in step 505 and transfers the statistical parameter(s) to DCE 11 via reverse channel 16 in step 510. This method is aimed at utilizing the data available in receiver 20 for the K samples (whereas the adaptation of the sign algorithm is based on one sample per data block of length K), and avoiding the need for synchronization between $\hat{e}(n)$ and $x(n-i)$. For example, let σ_e^2 be the variance of the error $e(n)$. Assuming the $e(n)$ is ergodic, σ_e^2 can be evaluated by:

$$\sigma_e^2 = \frac{1}{K} \sum_{n=1}^{n=K} e^2(n). \quad (3)$$

The adaptation of the i -th coefficient can be performed by:

$$f_i(n) = f_i(n-1) - \mu \hat{V}_i \quad (4)$$

where \hat{V}_i is an estimation of the gradient of σ_e^2 . Derivation of equation (3) yields the following estimation for the gradient:

$$\hat{V}_i = -\frac{2}{K} \sum_{n=1}^{n=K} \hat{e}(n) \hat{x}(n-i). \quad (5)$$

It is easy to see that by using this type of averaging in step 505 (hereafter referred to as gradient estimation), the variance of the minimum error in the estimation of the gradient is reduced by a factor of K . Note, that the misadjustment is proportional to this variance. Hence, the adaptation step size can be increased for obtaining a desired misadjustment, provided that the increased step size would ensure convergence. Increasing the step size would also accelerate the convergence of the pre-equalizer. Notice that gradient estimation is mostly effective for slow varying channels, where the channel is quasi-stationary for a period of K transmitted symbols. In this example, a set of values of \hat{V}_i for each coefficient is calculated by processor 125 in step 505 and then transmitted to DCE 11 in step 510. Processor 225 of DCE 11 recovers the statistical parameter(s), here represented by \hat{V}_i for each of the coefficients in step 515. Processor 225 then adapts the coefficient values, $f_i(n)$, ($i=0, 1, \dots, N-1$) of filter 215 in accordance with equation (4) in step 520.

A disadvantage of the above-described gradient estimation method is the need to transfer through the reverse channel different information for each coefficient, whereas in the sign algorithm only one bit is required for the adaptation of all the coefficients. As a result, the gradient estimation method uses more bandwidth than the above-mentioned use of a sign algorithm. However, the gradient

estimation method can be further modified so as to reduce the bandwidth required over the reverse channel. For example, requirements of the reverse channel data rate can be reduced by transferring over the reverse channel only a few bits per coefficient for representing \hat{V}_i . Indeed, even one bit may be considered (due to the accuracy of the estimation which is based on an average error). Yet another variation is to only adapt a few dominant coefficients of the pre-equalizer in the transmitter. Recall that the aim of performing adaptation of the pre-equalizer is eliminating error propagation, mostly caused by a few ISI coefficients. The remaining coefficients can be used to adapt a DFE in the receiver during the communications phase.

It should be noted that the mean square error, $E\{e^2(n)\}$, is small after the initialization process. As such, the mean squared error may serve as a figure-of-merit for the adaptation step size. Increase in the mean squared error may be interpreted as an increase in the misadjustment. In this case the pre-equalizer can increase the step size (using the reverse channel) for a short period in order to accelerate the adaptation.

The foregoing merely illustrates the principles of the invention and it will thus be appreciated that those skilled in the art will be able to devise numerous alternative arrangements which, although not explicitly described herein, embody the principles of the invention and are within its spirit and scope.

For example, as illustrated above, the adaptation signal can take many forms and only a few illustrative suggestions were described above. For example, the adaptation signal can represent a sequence of k-bit size words, where each k-bit size word represents the location of the first non-zero bit in a corresponding value of, e.g., $\hat{e}(n)$, as opposed to the value of $\hat{e}(n)$ itself. This approach, in effect, sends the most significant, non-zero bit(s) of the signal used for adaptation.

Further, although Tomlinson preceding was illustrated, any precoding scheme can be used in conjunction with the inventive concept. For example, the precoding specified by CCITT modulation standard V.34 could also be used with correspondingly straightforward changes in the receiver structure. This proposed scheme can be used in either an uncoded or coded communications system.

Also, although the invention is illustrated herein as being implemented with discrete functional building blocks, e.g., slicers, filters, etc., the functions of any one or more of those building blocks can be carried out using one or more appropriate programmed processors, e.g., the above-described pre-equalizer and processor of transmitter 10 can be implemented together in a suitably programmed digital signal processor.

What is claimed:

1. A data communications network having a startup phase of operation for establishing data communication and a communication phase of operation for communicating a data signal, the data communications network comprising:

- a transmitter;
- a receiver coupled to the transmitter via a transmit channel and a reverse channel;
- a precoder in the transmitter configured to filter a transmitted data signal $x(n)$ from the transmitter to the receiver, the precoder having a plurality of filter coefficients;
- a first processor in the receiver configured to generate an adaptation signal based upon an estimated error signal $\hat{e}(n)$, where the estimated error signal $\hat{e}(n)$ is defined by $\hat{e}(n)=y(n)-\hat{x}(n)$, where $\hat{x}(n)$ is an estimate of the transmitted data signal $x(n)$, and $y(n)$ is a received data

signal at the receiver, said received data signal $y(n)$ being the transmitted data signal $x(n)$ as altered by the transmit channel; and

a second processor in the transmitter configured to adapt the plurality of filter coefficients in response to the adaptation signal, the adaptation signal being received from the first processor via the reverse channel during said communications phase of operation.

2. The data communications network of claim 1, wherein the estimate of the transmitted data signal $\hat{x}(n)$ is generated by an infinite size slicer.

3. The data communications network of claim 1, wherein the adaptation signal is defined as the sign of $\hat{e}(n)$.

4. The data communications network of claim 1, wherein the adaptation signal is obtained by statistically processing $\hat{e}(n)$.

5. The data communications network of claim 3, wherein the second processor adapts the plurality of filter coefficients in response to the adaptation signal according to the formula $f_i(n+1)=f_i(n)+2\mu(\text{sgn}[\hat{e}(n)]\hat{x}(n-i))$ where $f_i(n)$ are the plurality of filter coefficients, and μ is an adaptation step size.

6. A transmitter apparatus having a startup phase of operation for establishing data communication with a receiver apparatus and a communication phase of operation for communicating a data signal to the receiver, the transmitter apparatus comprising:

a data output disposed to couple to a transmit channel which is coupled to the receiver apparatus;

a channel input disposed to couple to a reverse channel which is coupled to the receiver apparatus;

a data input disposed to couple to a data communications equipment, said data input receiving a data signal therefrom;

a precoder in the transmitter configured to filter a transmitted data signal $x(n)$, the precoder having a plurality of filter coefficients; and

a processor configured to adapt the plurality of filter coefficients in response to an adaptation signal received at said channel input during said communications phase of operation, the adaptation signal being generated based upon an estimated error signal $\hat{e}(n)$, where the estimated error signal $\hat{e}(n)$ is defined by $\hat{e}(n)=y(n)-\hat{x}(n)$, where $\hat{x}(n)$ is an estimate of the transmitted data signal $x(n)$, and $y(n)$ is a received data signal at the receiver, said received data signal $y(n)$ being the transmitted data signal $x(n)$ as altered by the transmit channel.

7. The transmitter apparatus of claim 6, wherein the estimate of the transmitted data signal $\hat{x}(n)$ is generated by an infinite size slicer.

8. The transmitter apparatus of claim 6, wherein the adaptation signal is defined as the sign of $\hat{e}(n)$.

9. The transmitter apparatus of claim 6, wherein the adaptation signal is obtained by statistically processing $\hat{e}(n)$.

10. The transmitter apparatus of claim 8, wherein the second processor adapts the plurality of filter coefficients in response to the adaptation signal according to the formula $f_i(n+1)=f_i(n)+2\mu(\text{sgn}[\hat{e}(n)]\hat{x}(n-i))$ where $f_i(n)$ are the plurality of filter coefficients, and μ is an adaptation step size.

11. A receiver apparatus having a startup phase of operation for establishing data communication with a transmitter apparatus and a communication phase of operation for receiving a transmitted data signal from the transmitter apparatus, the receiver apparatus comprising:

a data input disposed to couple to a transmit channel which is coupled to the transmitter apparatus;

a channel output disposed to couple to a reverse channel which is coupled to the transmitter apparatus; and a processor in the receiver apparatus configured to generate an adaptation signal based upon an estimated error signal $\hat{e}(n)$, where the estimated error signal $\hat{e}(n)$ is defined by $\hat{e}(n)=y(n)-\hat{x}(n)$, where $\hat{x}(n)$ is an estimate of the transmitted data signal $x(n)$, and $y(n)$ is a received data signal at the receiver, said received data signal $y(n)$ being the transmitted data signal $x(n)$ as altered by the transmit channel, the adaptation signal being transmitted to the transmitter device over the reverse channel while in the communications phase, the transmitter adapting a plurality of filter coefficients in a precoder in response to the adaptation signal.

12. The transmitter apparatus of claim 11, wherein the estimate of the transmitted data signal $\hat{x}(n)$ is generated by an infinite size slicer.

13. The transmitter apparatus of claim 11, wherein the adaptation signal is defined as the sign of $\hat{e}(n)$.

14. The transmitter apparatus of claim 11, wherein the adaptation signal is obtained by statistically processing $\hat{e}(n)$.

15. The transmitter apparatus of claim 13, wherein the second processor adapts the plurality of filter coefficients in response to the adaptation signal according to the formula $f_i(n+1)=f_i(n)+2\mu(\text{sgn}[\hat{e}(n)]\hat{x}(n-i))$ where $f_i(n)$ are the plurality of filter coefficients, and μ is an adaptation step size.

16. A data communications network having a startup phase of operation for establishing data communication and a communication phase of operation for communicating a data signal, the data communications network comprising:

a transmitter;

a receiver coupled to the transmitter via a transmit channel and a reverse channel;

a precoder in the transmitter configured to filter a data signal transmitted from the transmitter to the receiver, the precoder having a plurality of filter coefficients; means in the receiver for generating an adaptation signal based upon an estimated error signal $\hat{e}(n)$, where the estimated error signal $\hat{e}(n)$ is defined by $\hat{e}(n)=y(n)-\hat{x}(n)$, where $\hat{x}(n)$ is an estimate of the transmitted data signal $x(n)$, and $y(n)$ is a received data signal at the receiver, said received data signal $y(n)$ being the transmitted data signal $x(n)$ as altered by the transmit channel; and

means in the transmitter for adapting the plurality of filter coefficients in response to the adaptation signal, the adaptation signal being received from the means in the receiver via the reverse channel during said communications phase of operation.

* * * * *



US006373832B1

(12) **United States Patent**
Huang et al.

(10) Patent No.: **US 6,373,832 B1**
(45) Date of Patent: **Apr. 16, 2002**

(54) **CODE DIVISION MULTIPLE ACCESS
COMMUNICATION WITH ENHANCED
MULTIPATH DIVERSITY**

(75) Inventors: **Howard C. Huang; Laurence Eugene
Mallaender, both of Hoboken;
Giovanni Vannucchi, Middletown
Township Monmouth County, all of NJ
(US)**

(73) Assignee: **Lucent Technologies Inc., Murray Hill,
NJ (US)**

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/108,775**

(22) Filed: **Jul. 2, 1998**

(51) Int. Cl.⁷ **H04B 7/216**

(52) U.S. Cl. **370/342; 375/267; 455/69;
455/101**

(58) Field of Search **370/334, 335,
370/342, 414, 479; 375/221, 267, 299,
349; 455/88, 68, 69-500, 504, 506, 65,
70, 78, 562, 101**

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,829,777 A	8/1974	Muratani et al.	.....	325/4
5,280,472 A	1/1994	Glihousen et al.	.....	370/18
5,507,035 A	• 4/1996	Bantz et al.	.....	455/133
5,513,176 A	• 4/1996	Dean et al.	.....	370/335
5,574,989 A	11/1996	Watson et al.	.....	455/101
5,648,968 A	• 7/1997	Reudink	.....	370/335
5,781,541 A	• 7/1998	Schneider	.....	370/335
5,842,118 A	• 11/1998	Wood, Jr.	.....	455/101
5,886,987 A	• 3/1999	Yoshida et al.	.....	370/318

6,061,388 A * 5/2000 Saulnier et al. 375/200
6,131,016 A * 10/2000 Greenstein et al. 455/69

* cited by examiner

Primary Examiner—Melvin Marcelo

Assistant Examiner—Jasper Kwoh

(74) Attorney, Agent, or Firm—Wilford L. Wisner

(57) **ABSTRACT**

A system, a transceiver, and methods for code division multiple access (CDMA) communication. The system includes first and second code division multiple access transceivers. The first code division multiple access transceiver has a plurality of antennas disposed to provide transmission via a plurality of paths and the second code division multiple access transceiver has a rake arrangement for processing a plurality of signals received at the rake arrangement with differing delays or other characteristics. A driving arrangement is provided for causing the first code division multiple access transceiver to use a relative few, e.g., one, of the plurality of antennas. When, however, an indication is obtained that an adequate number of resolvable signals are likely not received at the rake arrangement of the second transceiver, a circuit switches the driving arrangement to cause the first transceiver to use more of the plurality of antennas. In one implementation, the second transceiver sends a feedback signal indicating the number of useful signals being received and the first transceiver responds to the feedback signal by selecting and using a desirable number of transmit antennas. In an implementation suitable for a time-division duplexing (TDD) communication system, the first transceiver obtains the indication by inference from the fact that it is not receiving an adequate plurality of resolvable signals from the second transceiver. When the first transceiver obtains the indication, it drives the increased number of antennas either with respective delays or with different codes of the CDMA type.

27 Claims, 6 Drawing Sheets

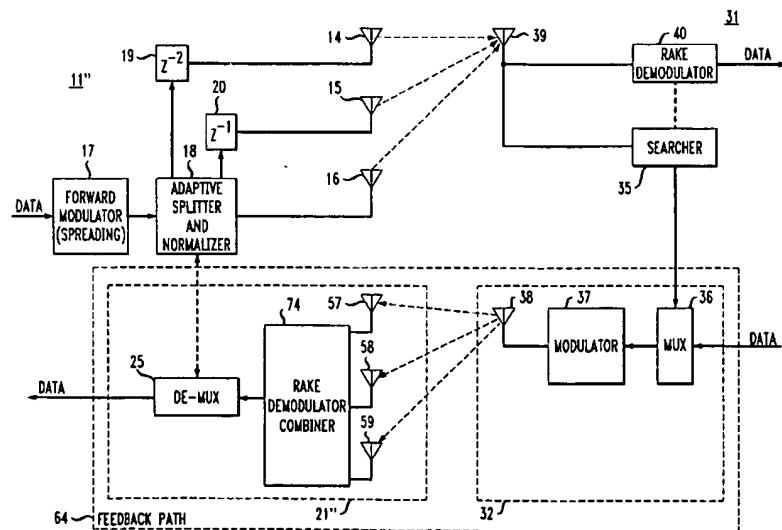
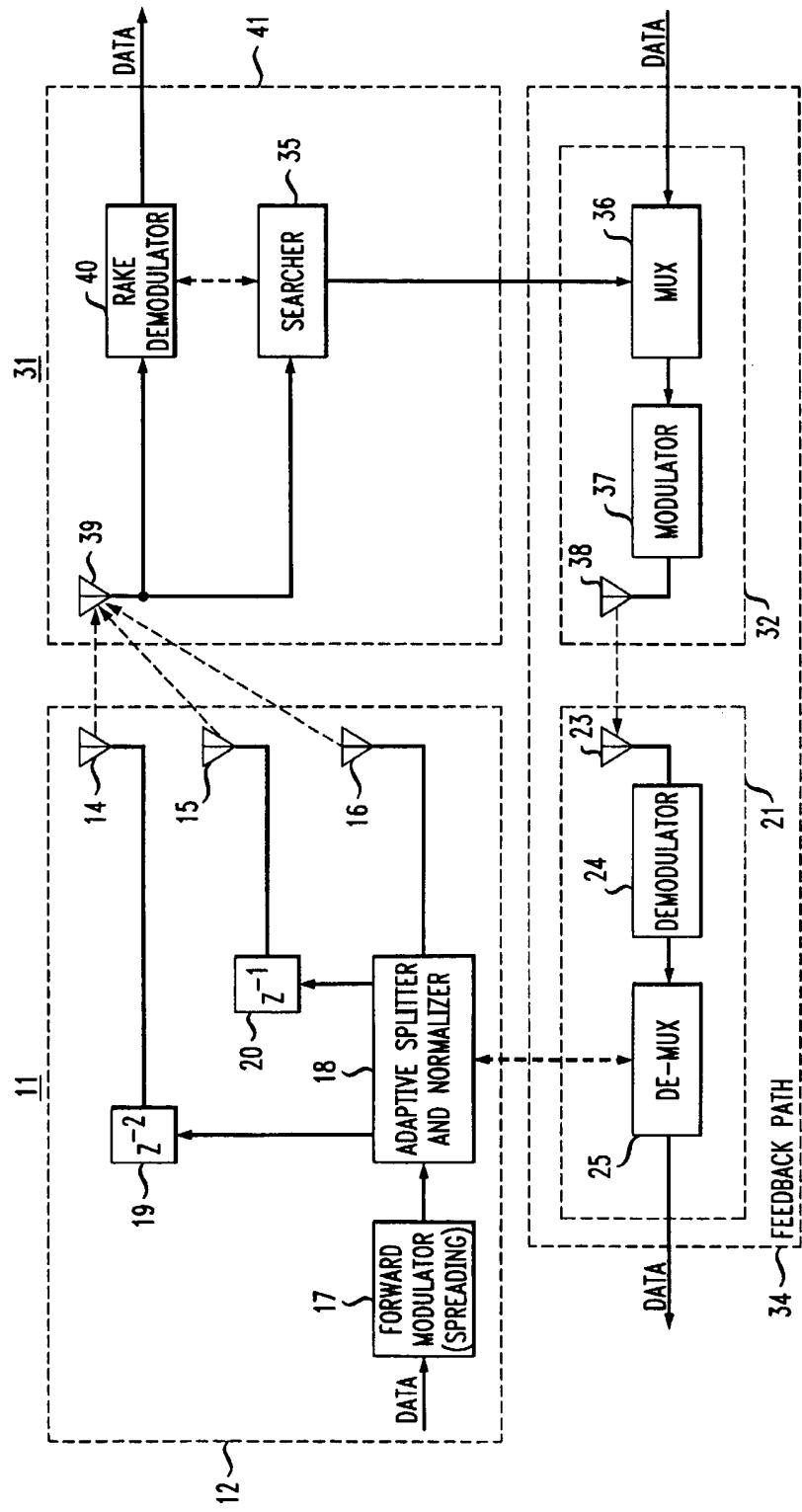
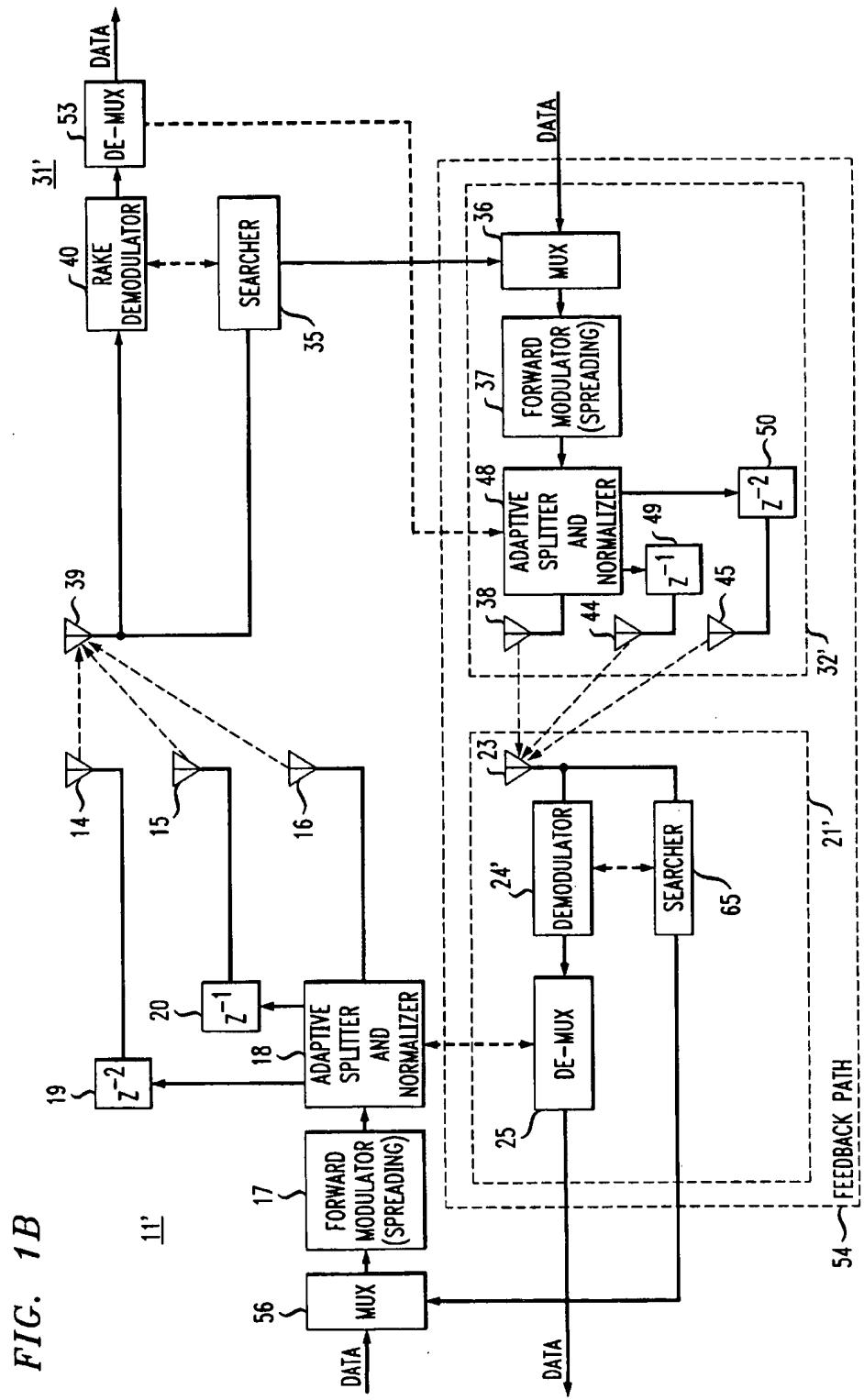


FIG. 1A





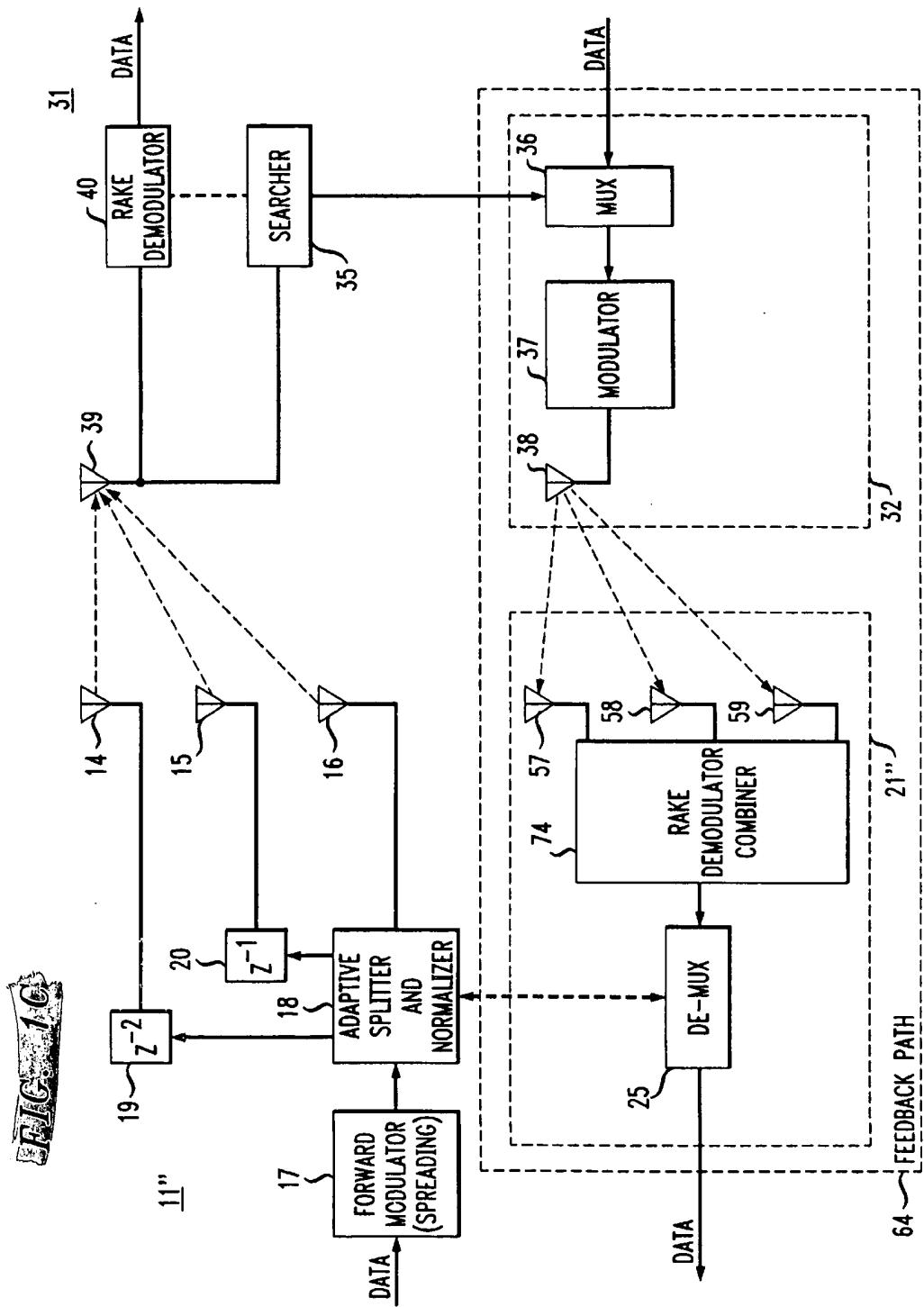


FIG. 2

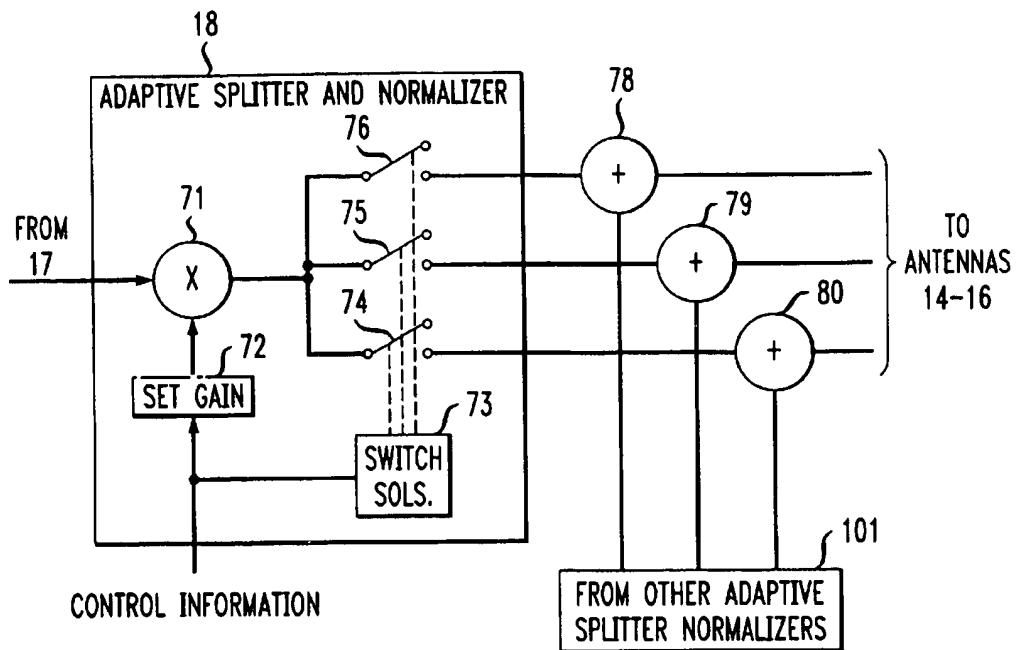
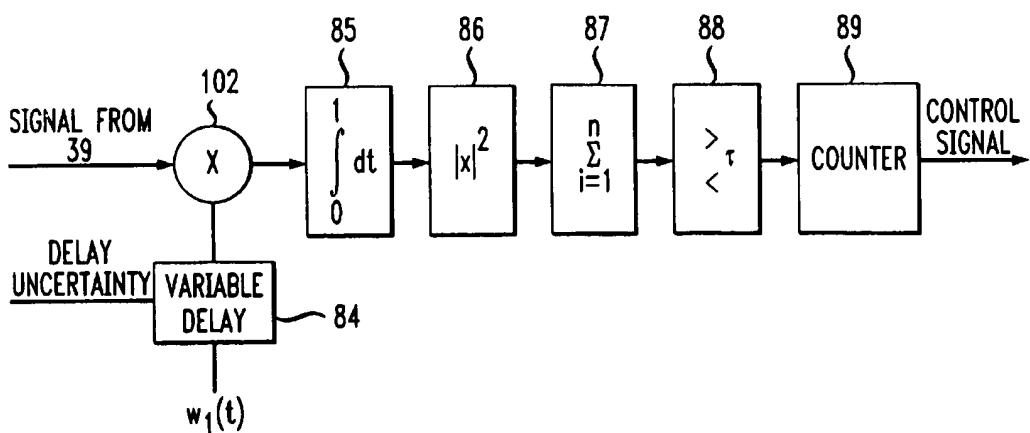
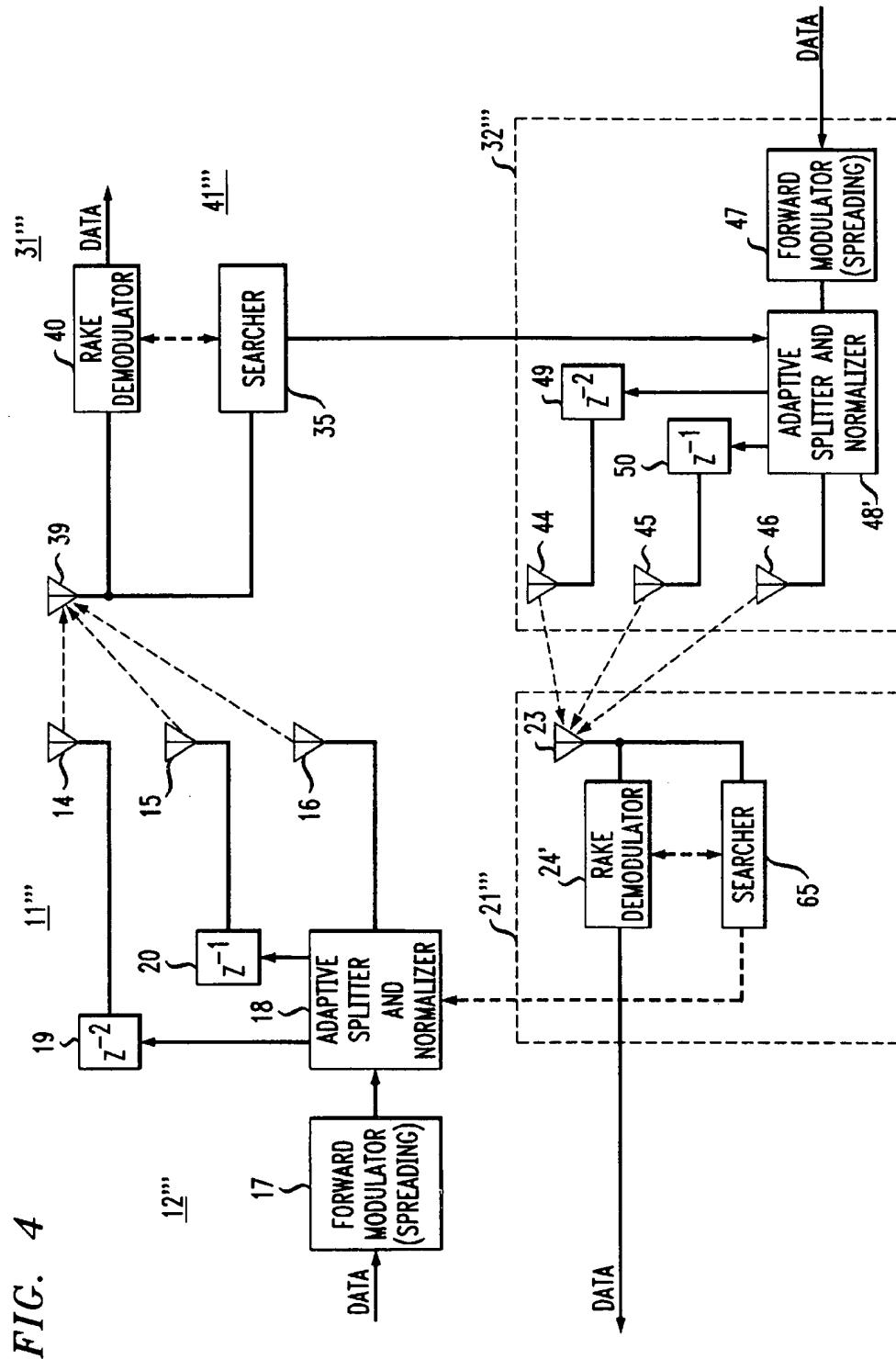
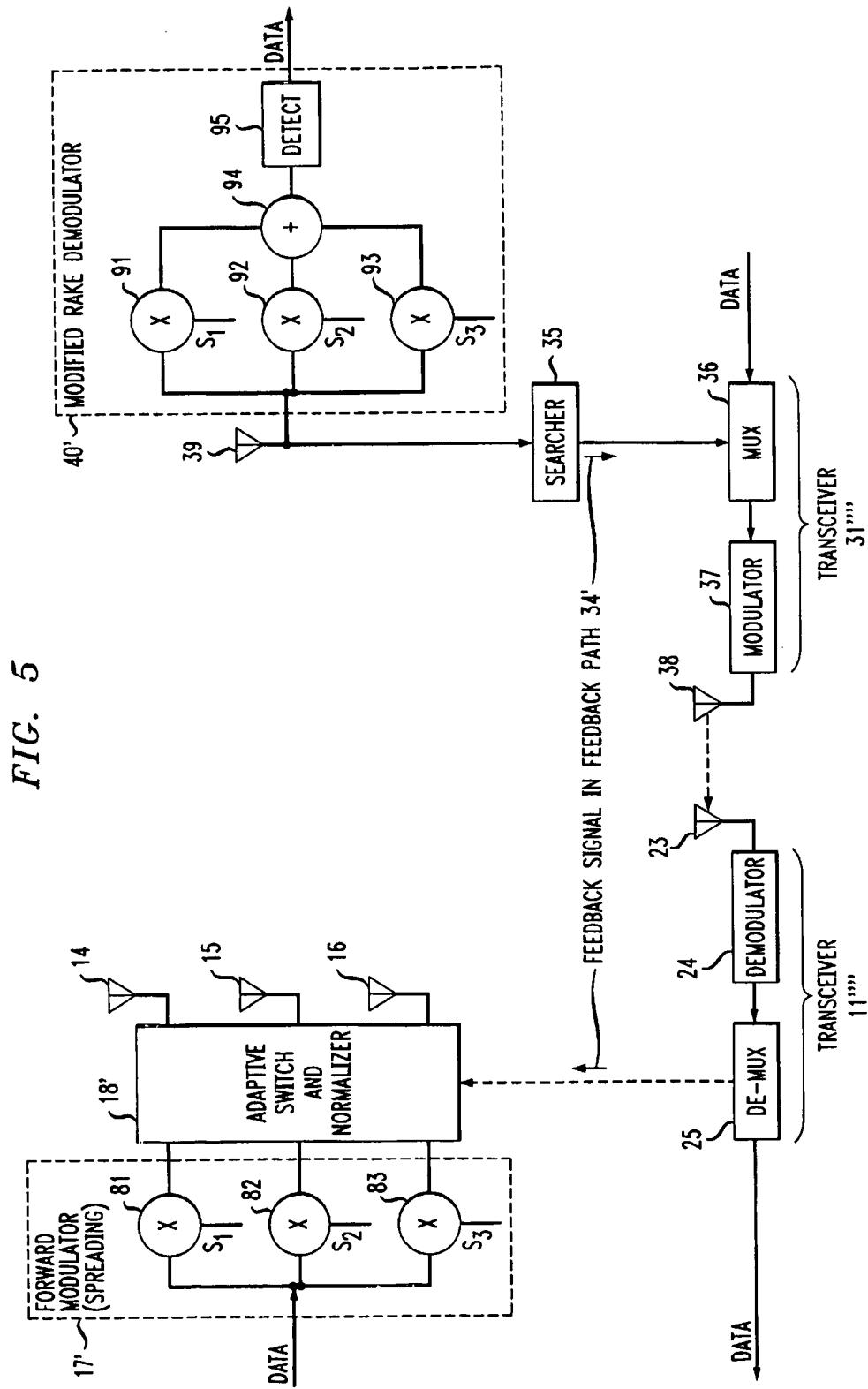


FIG. 3

SEARCHER







CODE DIVISION MULTIPLE ACCESS COMMUNICATION WITH ENHANCED MULTIPATH DIVERSITY

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to code division multiple access communication systems, code division multiple access transceivers, and to methods for operating them.

2. Discussion of the Related Art

Code Division Multiple Access (CDMA) has become one of the major technologies for digital wireless communications in the U.S. and worldwide. Growing demand for the service provided by CDMA has created a need for expanded data rates and higher system capacity. Working against the expansion of system capacity is the problem that some users may receive an inferior signal because of multipath fading that is a property of the particular channel in use. However, signal quality is improved by the use of diversity reception, in which multipath fading of a particular signal is overcome by receiving and combining two or more reflections of the signal. This technique works when two or more reflections are sufficiently separated in time so that they can be resolved, that is, distinguished and separated at the receiver. This desirable situation depends on the presence of radio reflections generated by the environment.

However, for some users in a CDMA system no set of resolvable signals ("no resolvable multipath") will exist. For example, this will occur at a particular receiver if the delay spread among the received reflections of the signal is less than one 'chip' duration. In this art, a 'chip' is a characteristic duration that is approximately equal to the inverse of the system bandwidth. When the delay spread among received reflections is less than one chip, the receiver cannot adequately distinguish and separate the signal reflections and therefore can provide no reduction in signal fading. This adverse situation can arise in both indoor and outdoor cellular systems. While it has been proposed to increase transmitter power to avoid such situations, such a tactic greatly reduces system capacity and increases interference. Alternatively, it is known that transmission diversity can be used, but in such proposed systems the cost in terms of reducing system capacity and increasing interference is significant.

SUMMARY OF THE INVENTION

According to the present invention, in a code division multiple access communication system, a first transceiver has on its transmitter side a plurality of antennas disposed to provide transmission using a plurality of paths; and a second transceiver has on its receiver side a "rake" arrangement for processing a multiplicity of received signal versions. Relatively few, ordinarily one, of the plurality of antennas in the first transceiver is used normally. When, however, the first transceiver obtains an indication that the receiver of the second transceiver is not receiving a sufficient number of resolvable signal versions, the first transceiver is switched to use more of the plurality of antennas. Thus, multipath fading is overcome and the capacity of the system is favorably affected, in that it is not necessary to increase total transmitted power and the diversity order is not increased unnecessarily for those users already obtaining adequate diversity signals through the radio-reflective multipath environment.

A first implementation of the invention feeds back a signal from the second transceiver to provide the indication that

resolvable multipath does not exist for the channel in use at its receiver side. The transmitter side of the first transceiver is then switched to use the increased number of antennas and thus provide transmission diversity of signals transmitted to the second transceiver.

A second implementation of the invention provides that the first transceiver detects at its receiver side that resolvable multipath does not exist at its receiver side for the channel in use for signals from the second transceiver. The first transceiver switches its own transmitter side to provide transmission diversity of signals transmitted to the second transceiver. Under the detected condition, it is at least likely that resolvable multipath does not exist at the receiver side of the second transceiver. Since in some systems, such as time-division duplexing (TDD) systems, the number of diversity paths on the up and down links will be identical, in the same period of time in which the first transceiver is switching, the second transceiver will have made the same adaptation. Thus, feedback is not necessary, as the requisite number of paths in both directions on the channel can be determined by each transceiver independently.

According to a further implementation of the invention, adaptive transmission diversity is provided by employing additional spreading codes, rather than delays, at the additional antennas on the transmitter side of each transceiver when no resolvable multipath exists.

According to a first aspect of the invention, a transceiver for code division multiple access communication has on its transmitter side a plurality of antennas disposed to provide transmission using a plurality of paths and on its receiver side a demodulator and demultiplexer for signals received from a remote transceiver. The transceiver has an arrangement to use relatively few, e.g., one, of the plurality of antennas normally. When, however, there is received an indication of no resolvable multipath, the arrangement switches the transceiver to use more of the plurality of antennas.

According to a second aspect of the invention, a transceiver for code division multiple access communication has on its transmitter side a signal splitter and modulator for data signals and has on its receiver side both a rake arrangement for attempting to separate a plurality of received signal versions from a remote transceiver and a searcher for searching for a plurality of resolvable signal versions. The searcher is connected from the rake arrangement to the signal splitter on the transmitter side to provide an indication signal for signal splitting whenever the searcher does not find a plurality of resolvable signal versions.

Various features of the invention reside in the particular arrangements for providing an indication signal and/or switching of antennas on a transceiver transmitter side and in the methods of operation, as will become clearer hereinafter.

BRIEF DESCRIPTION OF THE DRAWING

Further features and advantages according to both aspects of the invention will become apparent from the following detailed description, taken together with the drawing, in which:

FIG. 1A is a block diagrammatic showing of a first implementation of the invention;

FIG. 1B is a block diagrammatic showing of a second implementation of the invention;

FIG. 1C is a block diagrammatic showing of a third implementation of the invention;

FIG. 2 is a partially schematic and partially block diagrammatic showing of an implementation of the adaptive splitter and normalizer of FIGS. 1A-1C;

FIG. 3 is a partially schematic and partially block diagrammatic showing of an implementation of the searcher of FIGS. 1A-1C;

FIG. 4 is a block diagrammatic showing of a fourth implementation of the invention; and

FIG. 5 is a block diagrammatic showing of a fifth implementation of the invention.

DETAILED DESCRIPTION

The purpose of the disclosed technique is to sense which users have channels with insufficient diversity and to compensate therefor by providing diversity transmission to those users. The additional signals are generated with respective delays and with signal voltages adjusted so that constant or balanced total transmit power is achieved for any number of branches. The respective delay values of one chip and two chips must be at least that large. Each delay should differ from others by at least one chip duration. The antennas are physically spaced far apart enough (e.g., 20 wavelengths) so that independent fading paths are achieved at the receiver.

In FIG. 1A, a local transceiver 11 includes an arrangement for switching from the use of a single transmitter antenna, or a few such antennas, to a larger number of transmitter antennas on its transmitter side in response to an indication signal that a remote transceiver 31 is at least likely not receiving resolvable signal versions. Remote transceiver 31 has in its receiver 41 a rake arrangement and a searcher for searching for resolvable versions of a received signal. A connection to the transmitter side of transceiver 31 supplies, for multiplexing purposes, the indication signal that resolvable signal versions are not being received whenever that is the case. Transceivers 11 and 31 are illustratively not identical when transceiver 11 is a base station transceiver and transceiver 31 is a mobile transceiver. Then, transceiver 31 preferably does not carry multiple transmit antennas. In principle, however, the technique of the invention could be applied in both directions.

The local transceiver 11 has in its transmitter 12 a plurality of antennas 14, 15, and 16 for providing transmission using a plurality of paths and has in its receiver 21 an antenna 23, a demodulator 24 and a demultiplexer 25 for code division multiple access signals received from a remote transceiver 31. Illustratively, just one transmitter antenna of antennas 14, 15, and 16, e.g., antenna 16, is used under normal conditions. But when an indication is obtained that resolvable multipath does not exist, transceiver 11 includes means for switching transmitter 12 to use more antennas, illustratively, antennas 14 and 15 in addition to 16. In this implementation, 'resolvable multipath' refers to separable signals received via environmental reflections in different paths at remote transceiver 31, as determined by its receiver 41.

Feedback path 34 provides to transmitter 12 of transceiver 11 the indication that resolvable multipath does or does not exist at receiver 41 of transceiver 31. Feedback path 34 is indicated by the elongated dotted box in the lower portion of FIG. 1A and includes transmitter 32 of transceiver 31, receiver 21 of transceiver 11, and the radio transmission path between them.

Adaptive splitter and normalizer 18 is coupled to demultiplexer 25 in final portion of feedback path 34 to switch transmitter 12 to use more of antennas 14, 15, and 16 when it receives a signal that resolvable multipath does not exist.

Adaptive splitter and normalizer 18 feeds: (a) antenna 16 without delay, (b) antenna 15 with delay Z^{-1} via delay circuit 20, and (c) antenna 14 with delay Z^{-2} via delay circuit 19.

Feedback path 34 includes multiplexer 36, modulator 37, and antenna 38 in remote transmitter 32, as well as antenna 23, demodulator 24, and demultiplexer 25 in receiver 21 of local transceiver 11. In its initial portion, feedback path 34 is coupled in receiver 41 of remote transceiver 31 to searcher 35, which provides to multiplexer 36 in transmitter 32 a signal representative of the number of resolvable signal versions. Searcher 35 is coupled to antenna 39 and rake demodulator 40 to derive the number of resolvable received signals and to supply a signal reporting that number to feedback path 34 at multiplexer 36. The feedback path further includes in local transceiver 11 a connection from demultiplexer 25 in receiver 21 to adaptive splitter and normalizer 18 in transmitter 12 of local transceiver 11.

Demultiplexer 25 is coupled to adaptive splitter and normalizer 18 to supply the pertinent feedback signal to adaptive splitter and normalizer 18. Adaptive splitter and normalizer 18 splits the modulated data signal from forward modulator 17 into multiple parts for the increased number of antennas and normalizes them so that total transmitted power of transceiver 11 is not increased.

For the other direction of communication, that is from transceiver 31 to transceiver 11, the forward modulated data signal is multiplexed in transmitter 32 with the feedback signal to local transceiver 11. While transmitter 32 could be a mirror image of transmitter 12, and receiver 21 in transceiver 11 could be a mirror image of receiver 41 in transceiver 31, in general, that is not necessary. A more elaborate arrangement with some mirror image components is described hereinafter in connection with FIG. 1B.

In the operation of FIG. 1A, antenna 16 in transceiver 11 is used for transmission in the manner of a conventional CDMA transceiver, so long as the feedback signal does not indicate the failure of resolvable multipath at transceiver 31. This condition is consistent either with no signal from demultiplexer 25 or a signal from demultiplexer 25 that environmentally-provided resolvable multipath signals are being received by receiver 41 of transceiver 31. When a feedback signal indicating the failure of resolvable multipath is supplied from demultiplexer 25 to adaptive splitter and normalizer 18, then adaptive splitter and normalizer 18 activates antennas 14 and 15 through delays 19 and 20, respectively, and balances the signals at antennas 14-16. Antennas 14, 15, and 16 are spaced adequately (e.g., by 20λ) to ensure effective diversity transmission.

It should be noted that antennas 14-16, or one or more of them, as needed, are preferably simultaneously employed to transmit code division multiple access signals for a plurality of additional mobile receivers.

Receiver 21 of transceiver 11 could also monitor the presence or loss of resolvable multipath at receiver 21 through an arrangement (not shown) like that of receiver 41. Such loss of resolvable multipath may or may not coincide with loss of resolvable multipath in the other direction, as in general for CDMA systems the up-link and down-link paths need not be the same in both directions. Such an arrangement is not shown in FIG. 1A because the mobile terminal may not support multiple antennas. While three antennas are shown, it should be understood that the number of transmit antennas is adjusted for the particular channel experienced at any moment by a given user. Further, in addition to the feedback data signals as above described, it may be very desirable for some systems to transmit a delayed pilot signal for each antenna, as in an IS-95 downlink signal.

Advantageously, each receiver demodulates received signals with its standard rake arrangement, regardless of what is occurring at the remote transmitter.

Because of the operation of the present invention, the fingers of each rake demodulator are always fully exploited regardless of the environmental conditions of the channel used. The searcher 35 measures the power received at its receiver 31 for various delays, e.g., delays of a pilot signal, and reports the number of strong delays as control information. In the illustrated embodiment, this control information is sent via the feedback path 34 to the remote transceiver 11. Further, the feedback path may employ adaptive diversity control of known type.

In the implementation of FIG. 1B, adaptive transmission diversity is employed in both directions of transmission, as may be appropriate in an indoor PBX system with relatively fixed stations using relatively low-power radio transmission. While only the lower half of FIG. 1B is designated as a feedback path, it should be clear that the upper half of FIG. 1B is also a feedback path that can supply a signal indicating to remote transceiver 31' that the local receiver 21' of local transceiver 11' is finding no resolvable multipath. For this purpose, an additional searcher 65 is employed.

Searcher 65 supplies an indication signal to multiplexer 56 upstream of forward modulator 17. Transceiver 31' responds to the indication signal that is fed back to antenna 39 by separating the indication signal in demultiplexer 53, which applies that signal to an adaptive splitter and normalizer 48 like adaptive splitter and normalizer 18. Adaptive splitter and normalizer 48 drives antenna 38 and, in response to the signal indicating failure of resolvable multipath, also drives antennas 44 and 45 through respective one-chip and two-chip delays 49 and 50. In all other respects, the components and their relationships in FIG. 1B are like those in FIG. 1A.

In the implementation of FIG. 1C, the configuration and operation of transceiver 31 remains the same as in FIG. 1A. The transceiver 11" differs from transceiver 11 of FIG. 1A in that it employs variable receive diversity when environmental conditions do not provide resolvable multipath for signals it receives. Further, the implementation of FIG. 1C deploys all antenna arrays at the base transceiver. That is, no antenna arrays are needed at the mobile, or individual user, transceivers. More specifically, transceiver 11" has rake demodulator-combiner 74 connected from physically separated diversity reception antennas 57, 58, and 59 to demultiplexer 25. The receiver 21" of transceiver 11" gets spatial diversity when temporal diversity at its receiver side is not available. Further, any rake-demodulator it has (not shown) can be kept fully utilized. The operation of antenna array 57, 58, and 59 is independent of the operation of antenna array 14, 15, and 16. In all other respects, the components and their relationships in FIG. 1C are like those in FIG. 1A.

In FIG. 2 is shown one embodiment for adaptive splitter and normalizer 18. The modulated signal from modulator 17 is applied to multiplier 71, where it is multiplied by a signal from a gain setting circuit 72. Circuit 72 provides the power normalization for the number of active antennas, as derived from the feedback path control signal. The switch solenoids or solid-state switch drivers 73 individually and selectively activate the appropriate switch or switches 74-76 to activate the appropriate number of antennas according to the control signal. Summers 78-80 are inserted in the antennas paths because, at least where used in a mobile communication base station, the same antennas may be sending signals to other users. Each user requires an individual splitter-normalizer 101.

FIG. 3 shows an appropriate configuration for searcher 35, for which other configurations are known in the art. The received signal at antenna 39 is multiplied at multiplier 102 with a nominal matching waveform $W_0(t)$, such as a particular Walsh code combined with a particular random spreading sequence, at a plurality of possible arrival delays 84. The result is thereafter integrated, e.g., by the integration circuit 85, as is well-known in the art. Squarer 86 squares the result of the integration to estimate the energy, which summer 87 sums to give a medium term average. For each possible delay, these energies are compared to a threshold in threshold circuit 88. Counter 89 counts the number of delays whose energies exceed the threshold. This number, the number of strong paths, is fed back as a control information signal to the remote transmitting station.

In the implementation of FIG. 4, a feedback path such as feedback path 34 of FIG. 1A or feedback path 54 of FIG. 1B is not employed. For example, this alternative may be appropriate if transceiver 11", 31" are used in a TDD system or in another system in which the number of diversity paths on the up and down links will be identical. In this instance, each transceiver 11", 31" determines the existence of resolvable multipath independently based on the assumption that the transmission conditions in both directions are identical.

More specifically, in transceiver 11", when rake demodulator 24" and searcher 65 do not find a sufficient number of resolvable multipath signals received at antenna 23 of receiver 21", adaptive splitter and normalizer 18 of receiver 12" supplies signals to antennas 14 and 15 through delay circuits 19 and 20 and to antenna 16. This response provides transmission diversity to transceiver 31". This action occurs even though no feedback signal is available from transceiver 31". Likewise, in transceiver 31", when rake demodulator 40" and searcher 35 do not find a sufficient number of resolvable multipath signals received at antenna 39 of receiver 41", adaptive splitter and normalizer 48" supplies signals through delay circuits 49 and 50 to antennas 44 and 45 and to antenna 46. This response provides transmission diversity to transceiver 11". This action occurs even though no feedback signal is available from transceiver 11".

All other components and connections in FIG. 4 are the same as like numbered ones in FIGS. 1A-1C, 2, and 3, or adapted from similarly numbered ones in those figures. FIG. 4 differs from FIG. 1A in it lacks the feedback path and in the connection of searcher 65 in transceiver 11" to adaptive splitter and normalizer 18 and in the connection of searcher 35 in transceiver 31" to adaptive splitter and normalizer 48. If the up and down links are identical, the switching to provide additional diversity should be accomplished essentially simultaneously without feedback information.

In FIG. 5 is shown an implementation of the concept that additional diversity can be provided by the use of additional spreading codes at the separate antennas, instead of using different delays. FIG. 5 is arranged similarly to FIGS. 1A-1C and includes many of the same components, except for the absence of the delays. In the implementation of FIG. 5, additional diversity signals are supplied on different spreading codes. An original code S_1 is assumed, and additional codes S_2 and S_3 are given for illustration. In transceiver 11", separate branches are formed in modified forward modulator 17" prior to spreading by code division modulators 81-83, and a unique spreading sequence is assigned to each antenna. Forward modulator 47" is similarly modified. Adaptive switch and normalizer 18" provides power normalization and antenna switching. Rake demodulators 40" and 24" are modified from the corresponding ones

of FIG. 1. They include, for example, multipliers 91-93, as well as adder 94 and detect circuit 95.

In general, the method of the invention as applied in the implementation of FIG. 5 involves supplying additional diversity signals at a transceiver transmitter only when the transmitter has obtained an indication that resolvable multipath does not exist at the remote receiver. In that event, the same data signal is simultaneously modulated onto the different codes. The switch and normalizer 18', for example, selects the number of codes for this circumstance, maintaining constant power regardless of the number of codes and resulting modulated signals. These different modulated signals containing the redundant information are then sent to the widely separated antennas 14-16.

At the receiver of transceiver 31"'; the method includes using a rake arrangement, in this case, the modified rake arrangement 39, 40' to combine diversity signals from the several codes, each of which experiences independent fading, and possibly multiple delays of the same code. The searcher 35 must likewise detect all the delayed signal versions of each code. The receiver then notifies the transmitter via the feedback path how many strong signals it is receiving, and this number may be modified on the transmit side in response to the feedback via the adaptive switch and normalizer 18'. It is apparent that several codes bearing the same data are now available at the receiver of transceiver 31''''. It also should be apparent that a combined approach may be used in which delays and codes at both used to supply the diversity signals. These codes and/or results of demodulation may be combined by the rake arrangement to achieve a diversity advantage.

Further, additional spreading codes could be used instead of, or in addition to, delays in the TDD embodiment of FIG. 4.

One difference of the implementation of FIG. 5 or a modified FIG. 4 from those of FIGS. 1A-1C and previously-described FIG. 4 is that the rake arrangement must search over the best paths for several codes.

With respect to the implementations of FIGS. 1, 4, and 5, as well as various permutations and variations thereof, several mechanisms will enhance the system capacity. First, transmission to users with insufficient resolvable multipath will now require much less transmit power to achieve an acceptable error rate. Consequently, interference to other users will be reduced. The degree of this improvement depends on the fraction of users experiencing insufficient resolvable multipath. An additional subtle benefit of the invention concerns the advantageous alteration of the out-of-cell interference fading statistics. Currently, interference from the downlinks of the adjacent cells arrive at a handset via a small number of fading paths (possibly only one) and hence exhibit large variability in received power, contributing to outage. The out-of-cell interference generated by the transmission diversity exhibits reduced variability in received power and thus reduces outage.

The applicability of the principles of the present invention extends beyond the specifically-disclosed embodiments to other implementations and embodiments embraced within the appended claims and their equivalents, as will be clear to workers in this art and particularly to those who undertake to practice the invention.

What is claimed is:

1. A code division multiple access communication system, comprising:

first and second code division multiple access transceivers employing multipath diversity, the first code division

multiple access transceiver having a plurality of antennas disposed to provide transmission via a plurality of paths, the second code division multiple access transceiver having a rake arrangement for processing a plurality of versions of a signal received at the rake arrangement with differing delays or differing other characteristics;

means for operating said first code division multiple access transceiver to use a subset of the plurality of antennas in the absence of an indication that an adequate plurality of resolvable multipath versions of the signal are not received at the rake arrangement of the second code division multiple access transceiver; and

means for switching said first code division multiple access transceiver to use more of the plurality of antennas when an indication is obtained that an adequate plurality of resolvable multipath versions of the signal are not received at the rake arrangement of the second code division multiple access transceiver, said switching means comprising means for providing a feedback signal from the second code division multiple access transceiver to the first code division multiple access transceiver to provide the indication that the adequate plurality of resolvable multipath versions of the signal are not received at the rake arrangement of the second code division multiple access transceiver.

2. The code division multiple access communication system according to claim 1, wherein the first code division multiple access transceiver is a base station transceiver and the second code division multiple access transceiver is a mobile transceiver.

3. The code division multiple access communication system according to claim 2, further including means for driving the plurality of antennas of the base station transceiver with respective delays.

4. The code division multiple access communication system according to claim 2, further including means for driving the plurality of antennas of the base station transceiver with respective spreading codes.

5. A transceiver for code division multiple access communication, comprising:

on the transmitter side of the transceiver, a plurality of antennas disposed to provide transmission using a plurality of paths to provide multipath diversity; on the receiver side of the transceiver, a demodulator and demultiplexer for signals received from a remote transceiver;

means for operating the transmitter side of the transceiver to use a subset of the plurality of antennas in the absence of an indication that an adequate plurality of resolvable multipath signal versions are not received at the remote transceiver; and

means for switching the transceiver to use at least one more antenna of the plurality of antennas than is used in said subset when an indication is obtained that an adequate plurality of resolvable multipath signal versions are not received at the remote transceiver, comprising means for responding to a feedback signal from the remote transceiver providing the indication that an adequate plurality of resolvable multipath signal versions are not received at the remote transceiver.

6. The transceiver according to claim 5 that is a base station transceiver.

7. The transceiver according to claim 6, wherein the means for responding to the feedback signal from the remote transceiver comprises an adaptive splitter and normalizer connected from the demodulator and demultiplexer to the plurality of antennas.

8. The transceiver according to claim 6, further including, on its receiver side, a plurality of antennas, and wherein the demodulator is a rake demodulator-combiner connecting the plurality of antennas on its receiver side to the demultiplexer for diversity reception.

9. The transceiver according to claim 8, wherein the means for switching the transceiver comprises, on the transmitter side, an adaptive splitter and normalizer connected to the plurality of antennas.

10. The transceiver according to claim 5, further including means for driving the plurality of antennas with respective delays.

11. The transceiver according to claim 5, further including means for driving the plurality of antennas with respective spreading codes.

12. A method for operating first and second transceivers for code division multiple access communication, the first transceiver having on the transmitter side of the transceiver a plurality of antennas disposed to provide transmission employing multipath diversity using a plurality of paths and, on the receiver side of the transceiver, a demodulator and demultiplexer for signals received from the second transceiver, comprising the steps of:

operating the transmitter side of the first transceiver to use a subset of the plurality of antennas in the absence of an indication that a signal transmitted from the transmitter side does not provide an adequate plurality of resolvable multipath signal versions at the second transceiver; and

switching the transmitter side of the first transceiver to use more of the plurality of antennas when an indication is obtained that the signal transmitted from the transmitter side does not provide an adequate plurality of resolvable multipath signal versions at the second transceiver, comprising the step of responding to a feedback signal from the second transceiver providing the indication that the second transceiver is not receiving the adequate plurality of resolvable multipath signal versions.

13. The method of operating first and second transceivers according to claim 12, wherein the first transceiver is operated as a base station transceiver, the second transceiver being operated as a mobile transceiver.

14. The method of operating first and second transceivers according to claim 13, wherein the step of responding to a signal from the second transceiver comprises adaptively splitting and normalizing a modulated data signal for transmission from the plurality of antennas.

15. The method of operating first and second transceivers according to claim 13, further including the step of providing diversity reception for signals from the second transceiver.

16. The method of operating a transceiver according to claim 12, further including the step of driving the plurality of antennas with respective delays.

17. The method of operating first and second transceivers according to claim 12, further including the step of driving the plurality of antennas with respective spreading codes.

18. A method for operating a code division multiple access communication system including first and second code division multiple access transceivers, the first code division multiple access transceiver having a transmitter side having a plurality of antennas disposed to provide transmission employing multipath diversity via a plurality of paths, the second code division multiple access transceiver having a receiver side having a rake arrangement for processing a plurality of multipath versions of a signal received at the rake arrangement with differing delays or differing other characteristics, the method comprising the steps of:

operating the transmitter side of the first code division multiple access transceiver to use a subset of the plurality of antennas in the absence of an indication that resolvable multipath is not obtained at the rake arrangement of the second code division multiple access transceiver; and

switching the transmitter side of the first code division multiple access transceiver to use at least one more antenna of the plurality of antennas than is used in said subset when an indication is obtained that resolvable multipath is not obtained at the rake arrangement of the second code division multiple access transceiver, comprising the step of providing a feedback signal from the second code division multiple access transceiver to the first code division multiple access transceiver to provide the indication that resolvable multipath is not obtained at the rake arrangement of the second code division multiple access transceiver.

19. The method of operating a code division multiple access communication system according to claim 18, wherein the step of operating the first code division multiple access transceiver comprises operating it as a base station transceiver, the method further including the step of operating the second code division multiple access transceiver as a mobile transceiver.

20. The method of operating a code division multiple access communication system according to claim 18, further including the step of driving the increased number of antennas with respective delays.

21. The method of operating a code division multiple access communication system according to claim 18, further including the step of driving the increased number of antennas with respective spreading codes.

22. A mobile transceiver for code division multiple access communication employing multipath diversity, comprising:

on the transmitter side of the mobile transceiver, a multiplexer and modulator for data signals;
on the receiver side of the mobile transceiver, a rake arrangement for separating a plurality of multipath versions of a signal received from a remote base station transceiver; and
a searcher connected from the rake arrangement to the multiplexer to provide a feedback signal for multiplexing for transmission to the remote base station transceiver whenever the searcher does not find resolvable multipath at the rake arrangement, the feedback signal indicating absence of resolvable multipath.

23. A method for operating a mobile transceiver for code division multiple access communication employing multipath diversity, comprising the steps of:

multiplexing and modulating data signals for transmission to a remote base station transceiver;
demultiplexing and demodulating signals from the remote base station transceiver; and
searching for a plurality of resolvable multipath signal versions from the remote base station transceiver and providing a feedback signal for the multiplexing and modulating step indicating the absence of resolvable multipath whenever a plurality of resolvable multipath signal versions are not found.

24. A method for operating a system for code division multiple access communication employing multipath diversity, comprising the steps of:

determining the presence or absence of resolvable multipath at a receiver of a first transceiver of two communicating transceivers;
feeding back from a transmitter of the first transceiver to a receiver of a second transceiver of the two commun-

11

nicating transceivers a feedback signal indicating the lack of resolvable multipath at the first transceiver; and transmitting additional multipath signals from the second transceiver toward the first transceiver to enhance the existence of resolvable multipath at the first transceiver. 5

25. The method according to claim 24, wherein the step of feeding back a feedback signal comprises multiplexing said feedback signal with other signals for transmission from the transmitter of the first transceiver to the receiver of the second transceiver.

26. A system for code division multiple access communication employing multipath diversity between first and second communicating transceivers, comprising:

the first and second communicating transceivers;

means for determining that a lack of resolvable multipath exists at a receiver of the first transceiver; 15

12

means for feeding back from a transmitter of the first transceiver to a receiver of a second transceiver of the two communicating transceivers a feedback signal indicating the lack of resolvable multipath at the first transceiver; and

means for transmitting additional multipath signals from the second transceiver toward the first transceiver to enhance the existence of resolvable multipath at the first transceiver.

10 27. The system according to claim 26, wherein the means for feeding back a feedback signal comprises means for multiplexing said feedback signal with other signals for transmission from the transmitter of the first transceiver to the receiver of the second transceiver.

* * * * *